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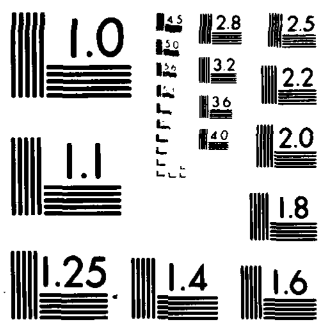

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HIGH BYPASS TURBOFAN COMPONENT DEVELOPMENT
MODIFICATION I - FINAL REPORT

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Aircraft Engine Group
General Electric Co.
Lynn, Massachusetts 01910

February 1980

Technical Report AFWAL-TR-80-2011
Final Report for Period June 1979 - October 1979

Approved for public release, distribution unlimited.

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The aerodynamic and mechanical redesign of a small, high through-flow, single stage fan rotor to increase its design-point airflow rate was completed. Since the original design exhibited excellent aeromechanical characteristics, the redesign was confined to changes in the blade meanline angle; parameters such as maximum thickness-to-chord ratio, thickness distribution, aspect ratio, and solidity being unchanged from the original design.

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20. Abstract - Continued

Procurement of the redesign fan rotor has been completed on schedule, thus fulfilling the requirements of this contract.

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LIST OF ILLUSTRATIONS

SUMMARY

The effort described in this final report was conducted under Amendment 1 of the High Bypass Turbofan Component Development Contract, USAF Contract F-33615-78-C-2060. The work-scope of this Contract amendment consists of the redesign and procurement of a small, high through-flow, single stage fan rotor. Effort was initiated on 14 May 1979 and will terminate with the approval and distribution of this final report.

The Contractor designed and tested a high through-flow fan component in 1978 and 1979. The performance of the fan was, in general excellent, but was two percent low in design-point airflow. Analysis of the test data and blade-to-blade flow field indicated that the blade suction surface from the leading edge to the passage mouth region was too close, resulting in inadequate area to pass the design airflow. The purpose of this program is to redesign the blade of the fan to meet the design airflow with the original blade thickness distribution and to purchase a new rotor blisk (integral blade and disk) which incorporates the design change.

INTRODUCTION

A single-stage fan, consisting of a rotor and stator for a small flow size turbofan engine, was designed to pass a flow per annulus area of 44.0 lb/sec-ft^2 based upon the rotor inlet annulus. The design point of the fan is as follows:

Corrected Airflow,	$W\sqrt{\theta}/\delta$	(lbm/sec)	14.65
Flow per Annulus Area,	W/A	(lbm/sec/ft^2)	44.0
Tip Speed,	UT	(ft/sec)	1600.
Pressure Ratio,	P/P		2.04

The rotor blade was designed with thicknesses considered necessary to satisfy aeromechanical requirements of encountering no blade instabilities throughout the entire operating range both with uniform and distorted inlet flow and with adequate leading edge thickness to withstand normal environmental conditions.

Component testing, under full atmospheric inlet conditions with both uniform and distorted flow, has indicated the aeromechanical requirements were entirely satisfied. Performance to 95% of design speed was excellent. However, at 100% corrected speed where the relative inlet Mach number at the rotor tip exceeded 1.70, the airflow was 2 percent below the design level, as shown in Figure 1 (pg 9).

Analysis of the test data and blade-to-blade flow field have indicated that the blade suction surface from the leading edge to the passage mouth region had inadequate area to pass design flow.

Since meeting design airflow was an important objective, it was desirable to demonstrate that design airflow could be achieved by modifying the blade suction surface. This approach involves the following four tasks:

1. Quantify the change in suction surface angle required to meet design airflow through a Method of Characteristics Analysis.

2. Incorporate this change into a blade redesign. The redesign involves blade meanline angle change, all other parameters are unchanged.

3. Procure a new blisk incorporating the blade redesign.

4. Test the blade with and without inlet airflow distortion to determine the effect of the redesign on fan performance.

The method of characteristics analysis, the blade redesign and the procurement of the blisk are covered by this Contract.

DESCRIPTION OF TECHNICAL WORK

FAN ROTOR AERODYNAMIC DESIGN

Method of Characteristics

It is well known that the method of characteristics is the most accurate numerical technique for solving hyperbolic partial differential equations. The relative inlet flow of a transonic compressor rotor is supersonic in the outer region. Since the mathematical character of the supersonic flow is hyperbolic with Mach lines representing natural characteristics, the above method can be conveniently adopted for those regions where the relative flow is supersonic. For the redesign of the fan rotor, this method was applied to the six outer streamlines for generating the suction surface profile of the entrance region.

Before describing the approach adopted for the application of this technique to estimate the flow capacity of the supersonic region of the rotor, it is relevant to provide details of the inlet flow. Typically, the relative supersonic flow incident to the rotor will have a subsonic axial flow component. Therefore, a system of waves emanates from the leading edges of the blade row which propagates upstream of successive blades. The last Mach wave which originates on the suction surface of one blade and lies entirely upstream of succeeding blade is normally termed the "first covered wave" or the limiting characteristic (Figure 2, pg 10). This limiting chracteristic is the downstream boundary of the entrance (or induction) region. From a physical point of view, only the blade suction surface upstream of the limiting characteristic can influence the flow within the entrance region. In fact, the waves originating from the suction surface modify the approaching flow and set up a condition known as "unique incidence" which is a characteristic of the supersonic rotor inlet flow with subsonic axial (or meridional) component. The adjustment of the flow to a "unique incidence" implies a mass balance between the entrance flow and the flow across the first covered wave. This serves as a criterion for establishing the mass flow capacity in the supersonic region of the rotor.

The actual development of the flow field in the supersonic inlet region of the rotor starts with the formation of a detached bow shock upstream of the blade leading edge, the strength and the shape of the shock being a function of the relative inlet Mach number and the blade leading edge thickness. Downstream of this shock the flow is supersonic in the entrance region except for a small region around the leading edge. This bow shock sets up an entropy gradient and makes the inlet flow rotational.

FAN ROTOR AERODYNAMIC DESIGN - Continued

Formally, the approach adopted for computing the flow field in the entrance region is as follows:

1. Using the blade leading edge thickness, and an initial estimate of the upstream relative Mach number and the flow angle, a bow shock is generated based on the Moeckel's model (Ref. W.E. Moeckel, "Approximate Method for Predicting Form and Location of Detached Shock Waves Ahead of Plane or Axially Symmetric Bodies"; NACA Tech Note 1921).

   The properties at the exit of this bow shock are computed with the aid of oblique shock relations.

2. Sonic point is located on the suction surface of the blade by fitting a wedge corresponding to the sonic angle. Flow properties at a point on the suction surface slightly downstream of the sonic point are established by using Prandtl-Meyer expansion.

3. The above suction surface point and the bow shock form the initial value line for generating the characteristics mesh in the entrance region. In the generated characteristics mesh, it is assumed that the flow is isentropic (but not homentropic) downstream of the bow shock. The mesh is adjusted until a first covered wave is accurately established.

4. Mass flow rate across the first covered wave is computed and is compared with the incoming mass flow rate.

5. If a discrepancy exists between the incoming mass flow and that across the first covered wave, the upstream flow conditions (Mach number and the flow angle) are modified; and Steps 1 through 4 are repeated till a convergence is achieved. The converged solution establishes the mass flow capacity and the unique incidence for any blade section.

Application to GE Fan Rotor

The mass flow capacity of the fan blade sections with supersonic inlet relative velocity was estimated using the "unique incidence" criterion described in the previous section. The suction surface profile in the entrance region of the blade was reshaped to improve the flow capability of the blade.

Figure 3 (pg 11) shows the computed mass flow capacities of the original and the redesigned rotors. The results are presented for streamlines 1 (tip), 3 and 6 (pitch) covering the flow region above the pitchline.

FAN ROTOR AERODYNAMIC DESIGN - Continued

It is seen from the results of this computation that a significant increase in the mass flow capacity is expected for the redesigned configuration. The major improvement has been concentrated in the flow-deficient area near the blade tip.

Figures 2 and 4 (pgs 10 and 12) show the characteristic mesh for streamline 1 of the original and redesigned blades, respectively. It is seen from these figures that an embedded shock appears in the entrance region of the original rotor due to the intersection of the characteristics of the same type. This embedded shock, which is a source of higher losses and hence lower flow capacity, has been eliminated in the new design.

Blade Meanline Design

Since the purpose of the rotor redesign was to improve its mass flow capacity, and the fan has previously demonstrated excellent aeromechanical characteristics, no alterations were made in parameters such as maximum thickness to chord ratio, thickness distribution, aspect ratio and solidity. The blade meanline angle was the only parameter varied in the redesign.

An axisymmetric model of the fan was utilized to establish the flow field through the rotor. Then a blade-to-blade analysis was performed which allows the designer to "customize" the design of airfoil sections for optimum performance.

The blade meanline in the entrance region was adjusted to produce the suction surface angles prescribed by the Method of Characteristics analysis. An alternate approximate way of ensuring that the blade section will pass the design mass flow is to keep the suction surface incidence $\hat{i}$ positive (see Figure 5, pg 13). The new and original designs are compared in Figure 6 (pg 14). Although the method is only approximate due to "simple wave" assumption inherent in the criterion, it provides a simple way to quantify the blade change.

Once the inlet region of the blade was re-established, the change was blended in to maintain the aerodynamic performance of the blade. Particular attention was paid to blade passage area ratios. One criterion is to ensure that the blade passage area distribution is adequate to swallow any normal shock upstream of the blade passage. The principle involved is the same as that used for the design of a supersonic wind tunnel with double throat. Failure to meet this criterion can result in operating the rotor in an unstarted mode which, in turn, can lead to a serious deterioration of the overall performance. The blade passage area distribution also controls the load distribution through the blade, and therefore, boundary layer behaviour.

FAN ROTOR AERODYNAMIC DESIGN - Continued

The desired area distribution can be achieved by controlling three basic area ratios; namely, AT/AI, AT/AM, and AT/AD. The first two area ratios (AT/AI and AT/AM) are sometimes termed "throat" and "starting" margins, respectively. The definition of these area ratios is given in Figure 7 (pg 15). Figures 8 and 9 (pgs 16-17) give the area ratios for the fan blade. The blade has also been modified in the hub region. The hub sections were opened near the leading edge to increase the throat margin to greater than 4 percent to assure that the hub can also pass design airflow.

Figure 10 (pg 18) shows a comparison of the meanline angles of the tip and pitch blade sections for the new blade and the original blade. Figure 11 (pg 19) shows corresponding meanline angles for the hub section.

Blade Sections for Manufacturing

The detailed blade sections were defined on streamlines as described in Blade Meanline Design (pg 5) and then stacked to generate plane sections for manufacturing. The new tip, pitch, and hub sections are compared to the original sections in Figures 12, 13, and 14 (pgs 20-22), respectively. The hot-to-cold deformation is the same as in the original blade since blade thickness was not changed. The new rotor (like the original) will be manufactured by machining the blades from a single forging, and therefore, producing an integral blade and wheel.

FAN ROTOR MECHANICAL DESIGN

Mechanical Design Summary

The redesigned fan rotor differs very little from the original design from mechanical design considerations. The airfoil load and load distribution in the disk rim area for the original design and the redesign are shown in Figure 15 (pg 23). Since the blisk material (AM 355) and number of airfoils (18) remain unchanged, and since the disk loading is practically identical, the original stress analysis is valid for the redesigned rotor.

Rotor Mechanical Design Point

The fan rotor design point is a design speed of 46,790 rpm (105% of 44,562 rpm). The assumed corresponding maximum disk temperature is 300°F.

FAN ROTOR MECHANICAL DESIGN - Continued

Stress Analysis

The load distribution, shown in Figure 15 (pg 23) was simulated by 10 discreet loadings acting on the shell joints, as shown in Figure 16 (pg 24). The model is conservative in that it permits the leading and trailing edges to grow freely. In reality, the airfoils act as stiffeners and prevent large rim deflections.

Since no effort was made to produce a flight-weight disk, the stresses are quite low, and the stiffness effect of the airfoils may be neglected.

The results of this analysis show that bore stresses do not exceed 100 Ksi, and the maximum stress at the connection of the aft shaft is 110 Ksi. Radial growth at the platform leading edge is 0.004 inches, and at the platform trailing edge is 0.006 inches.

FAN ROTOR PROCUREMENT

The redesigned fan rotor drawings and precision mylars of the airfoil sections were supplied to a machining vendor early in July, 1979. The integral bladed disk ("blisk") was completed in October, 1979. Photographs of the redesigned fan blisk are provided in Figures 17 through 20 (pgs 25-28). Condition of the hardware is considered excellent, with good dimensional control, surface finish, and smooth blending between the airfoils and the inner flowpath.

CONCLUSIONS

The objectives of the fan redesign and procurement have been met. The required increase in aerodynamic design point airflow rate was obtained by changes in the blade meanline angle, preserving the blade thickness distribution, maximum thickness-to-chord ratio, aspect ratio, and solidity of the original design, which demonstrated acceptable aeromechanical characteristics.

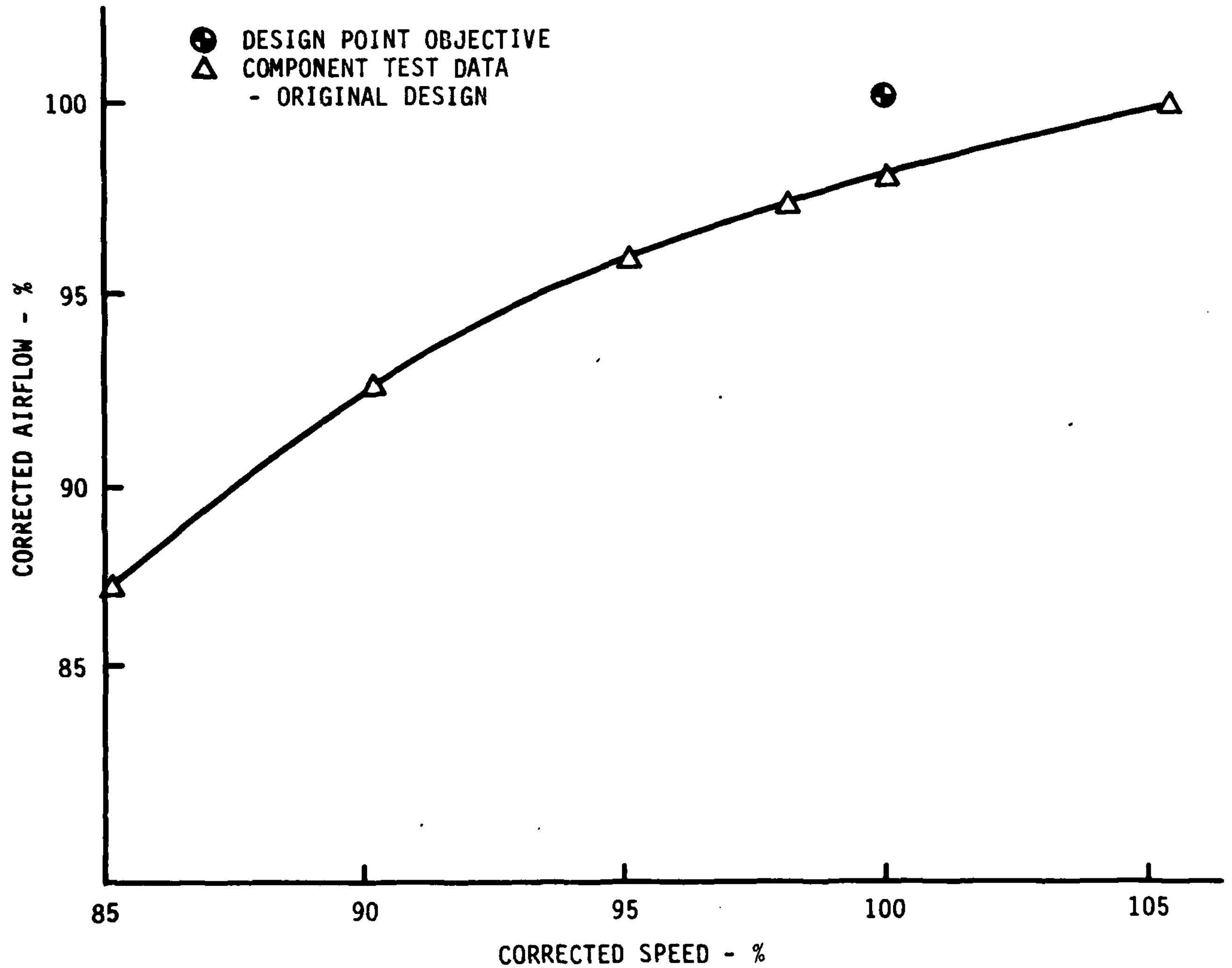

Figure 1. Fan Airflow vs Speed.

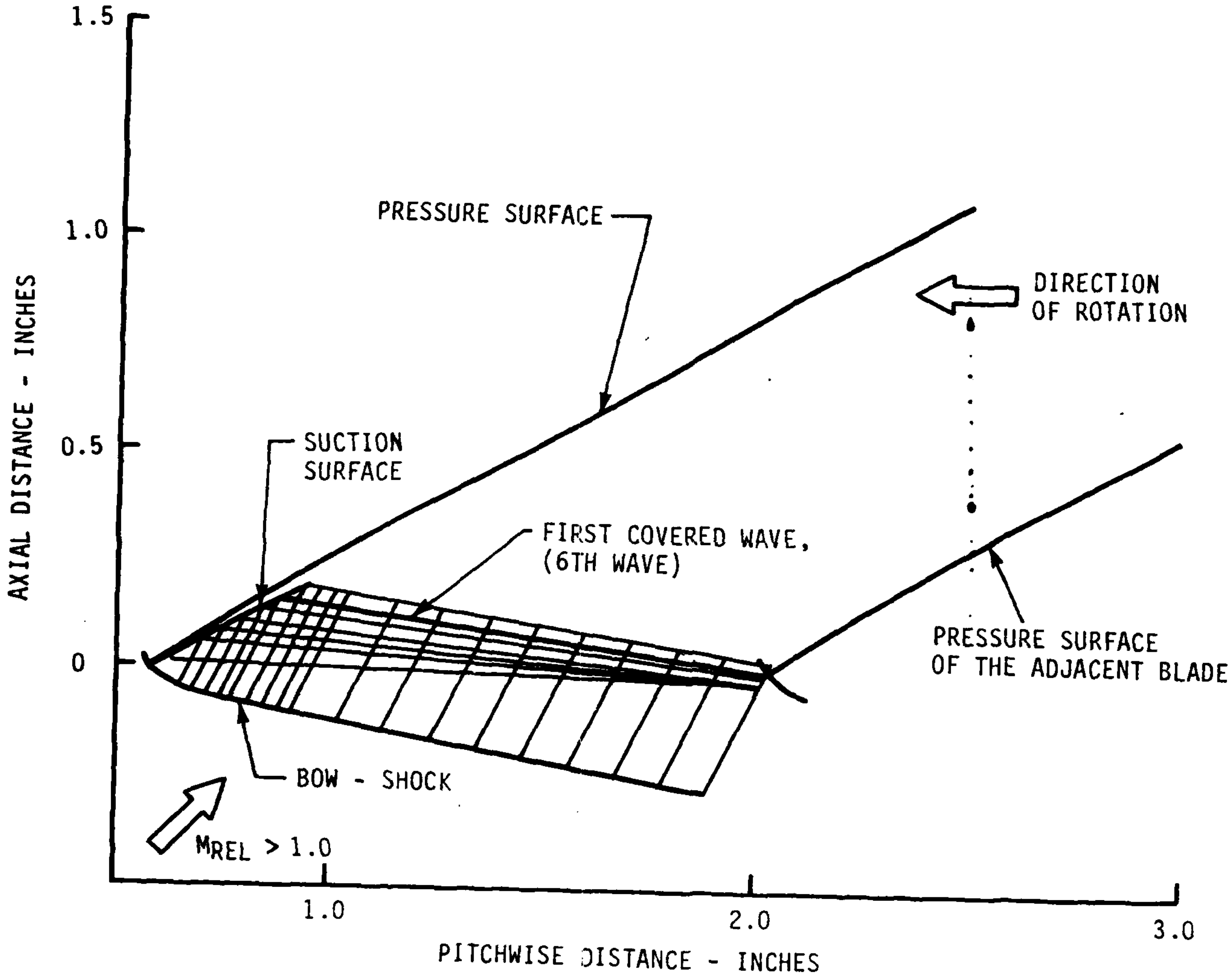

Figure 2. Fan Blade Bow Shock Pattern - Tip Section Original Design.

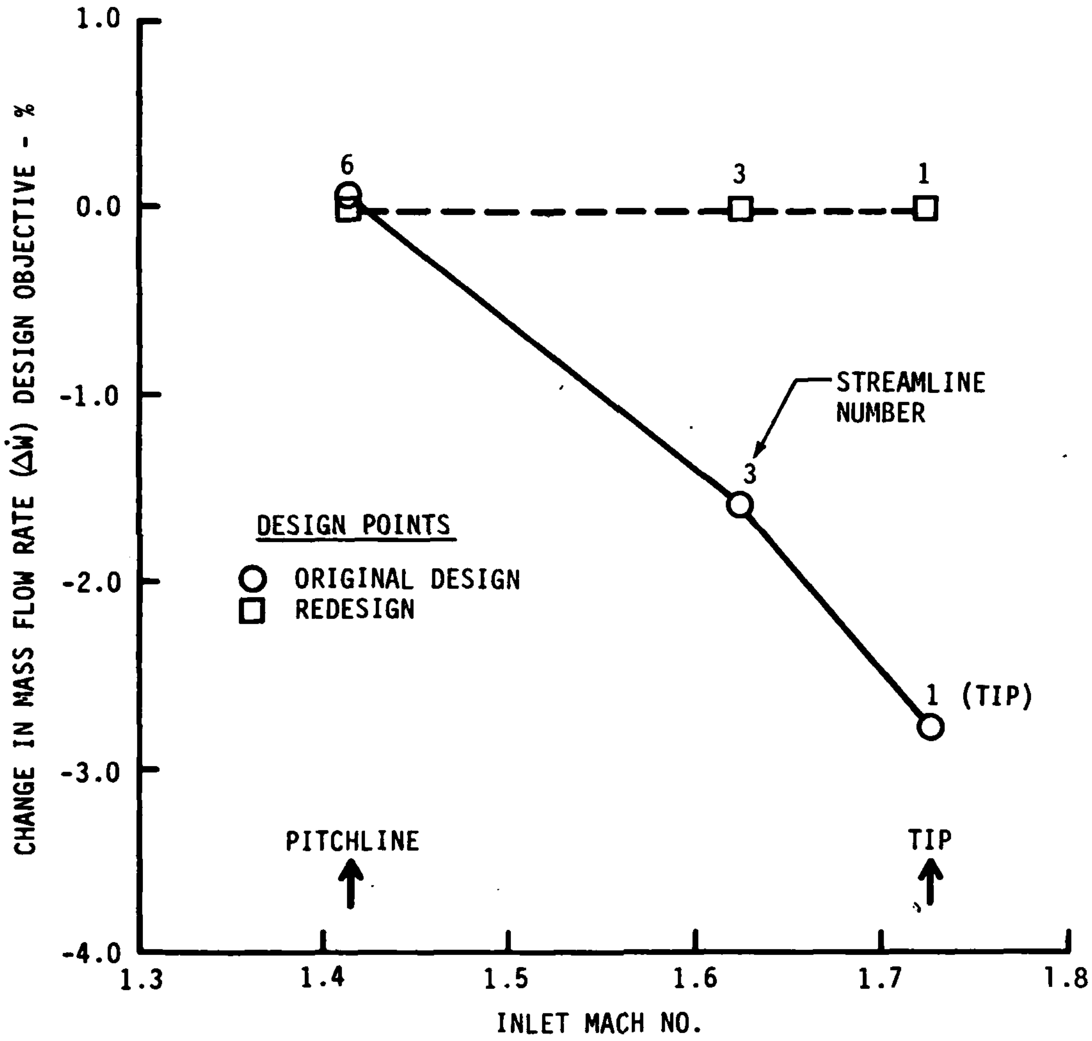

Figure 3. Fan Rotor Mass Flow Deviation.

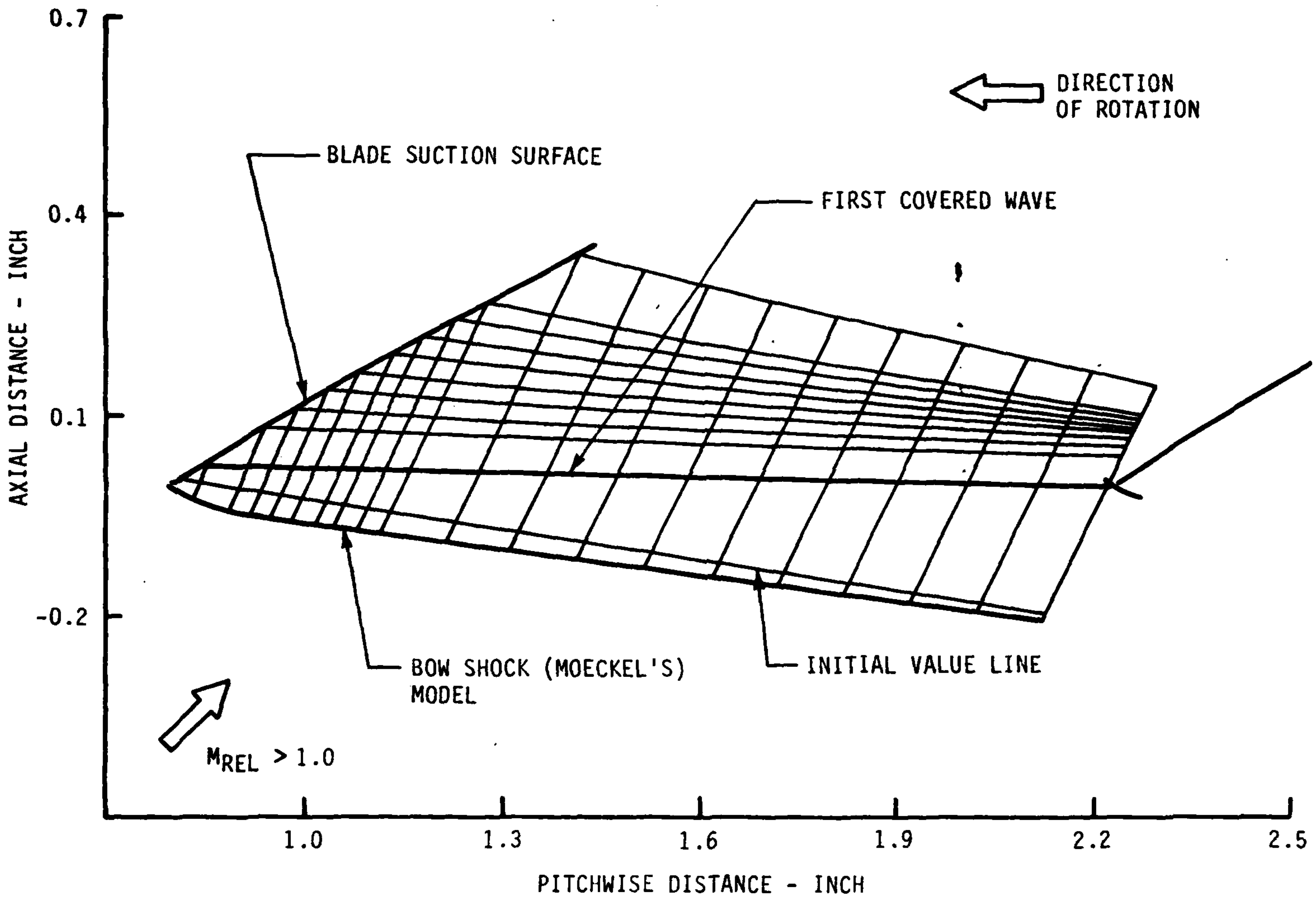

Figure 4. Redesigned Fan Blade Shock Pattern - Tip Section.

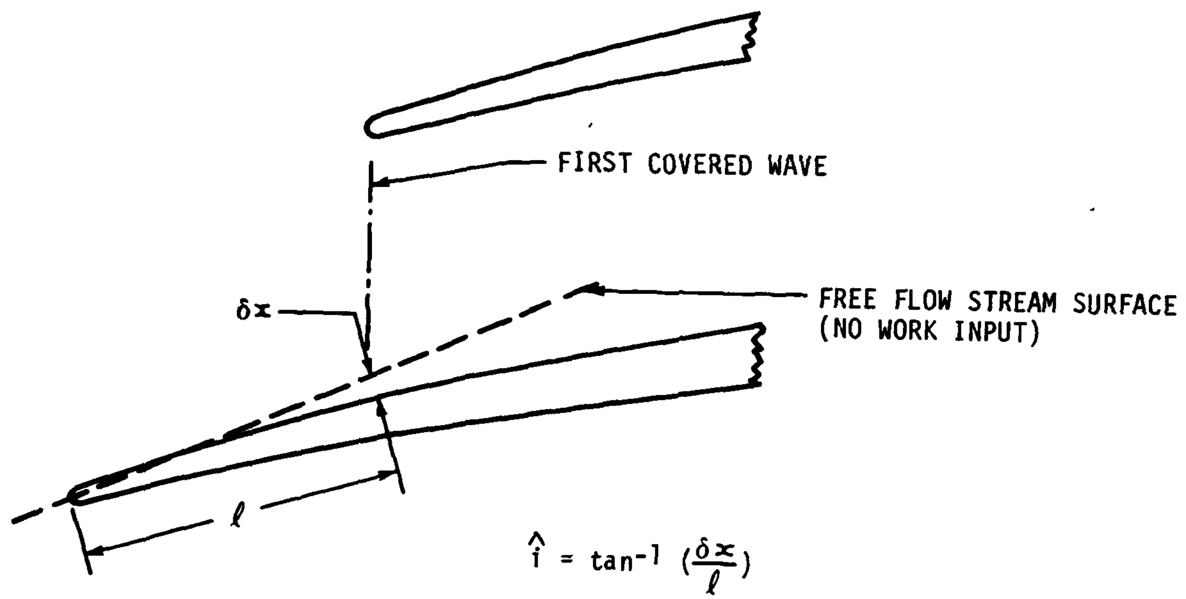

Figure 5. Suction Surface Incidence Definition.

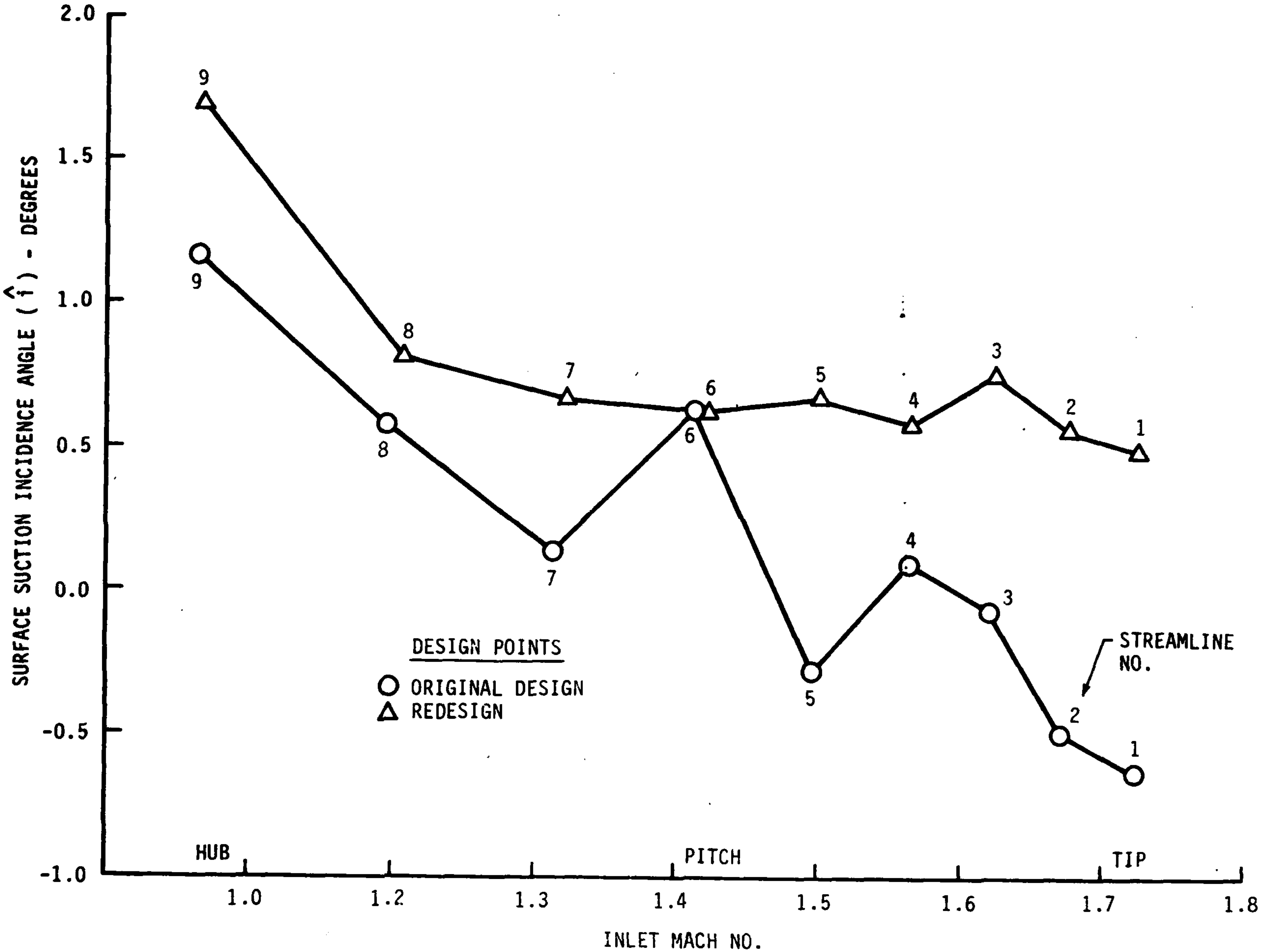

Figure 6. Fan Rotor Suction Surface Incidence.

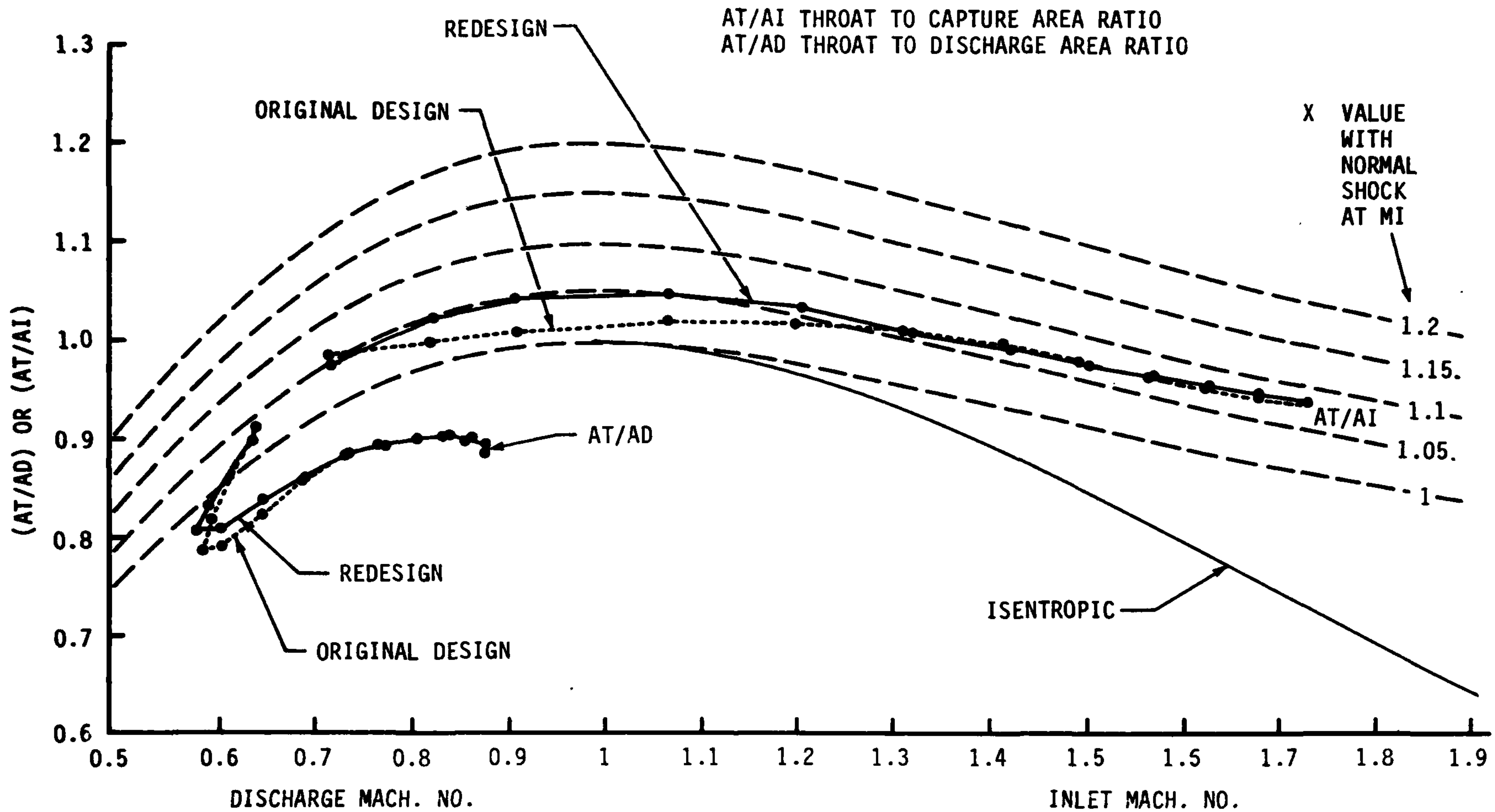

Figure 8. Fan Rotor Blade Passage Area Ratios.

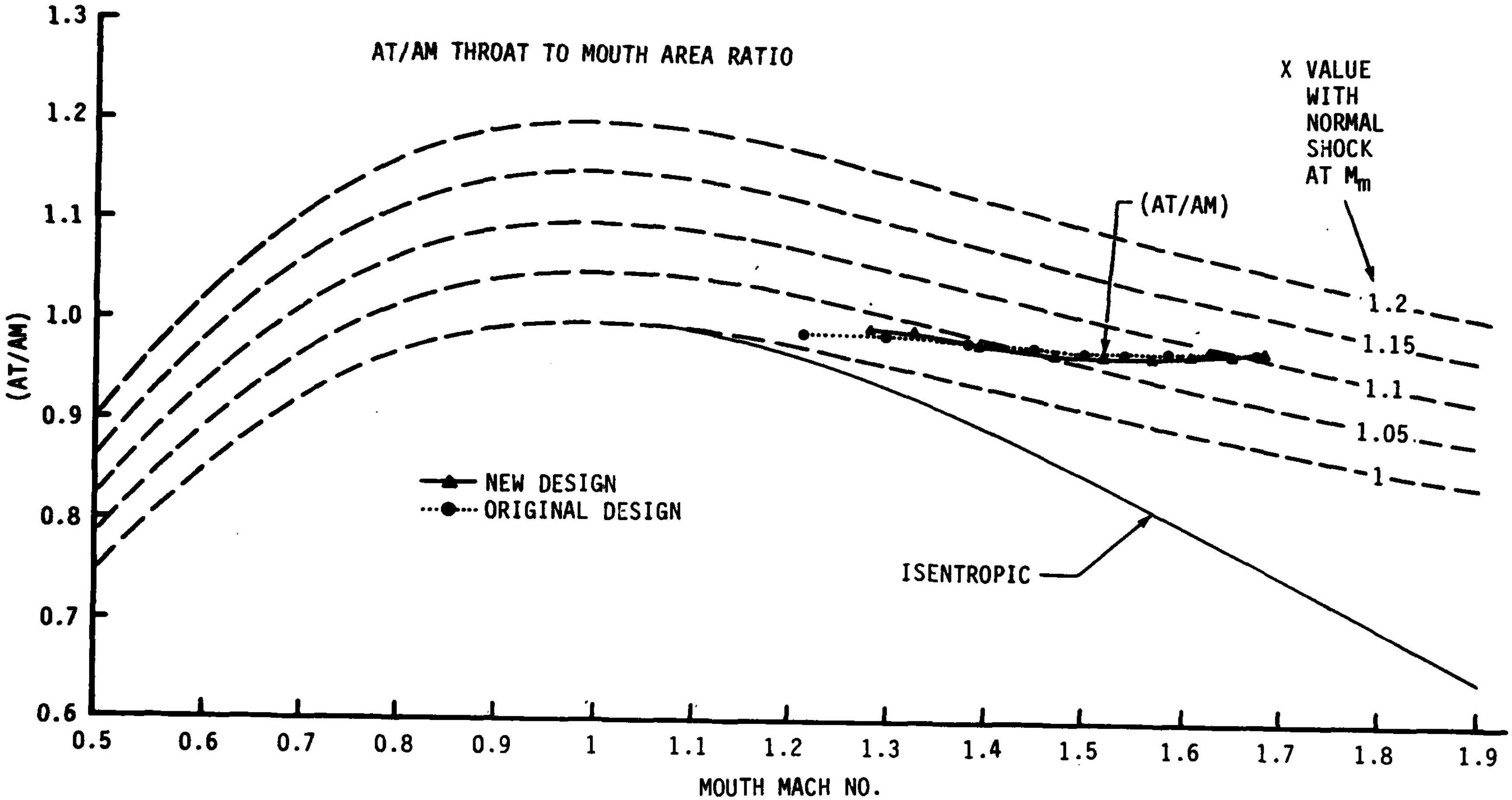

Figure 9. Fan Rotor Blade Passage Area Ratios.

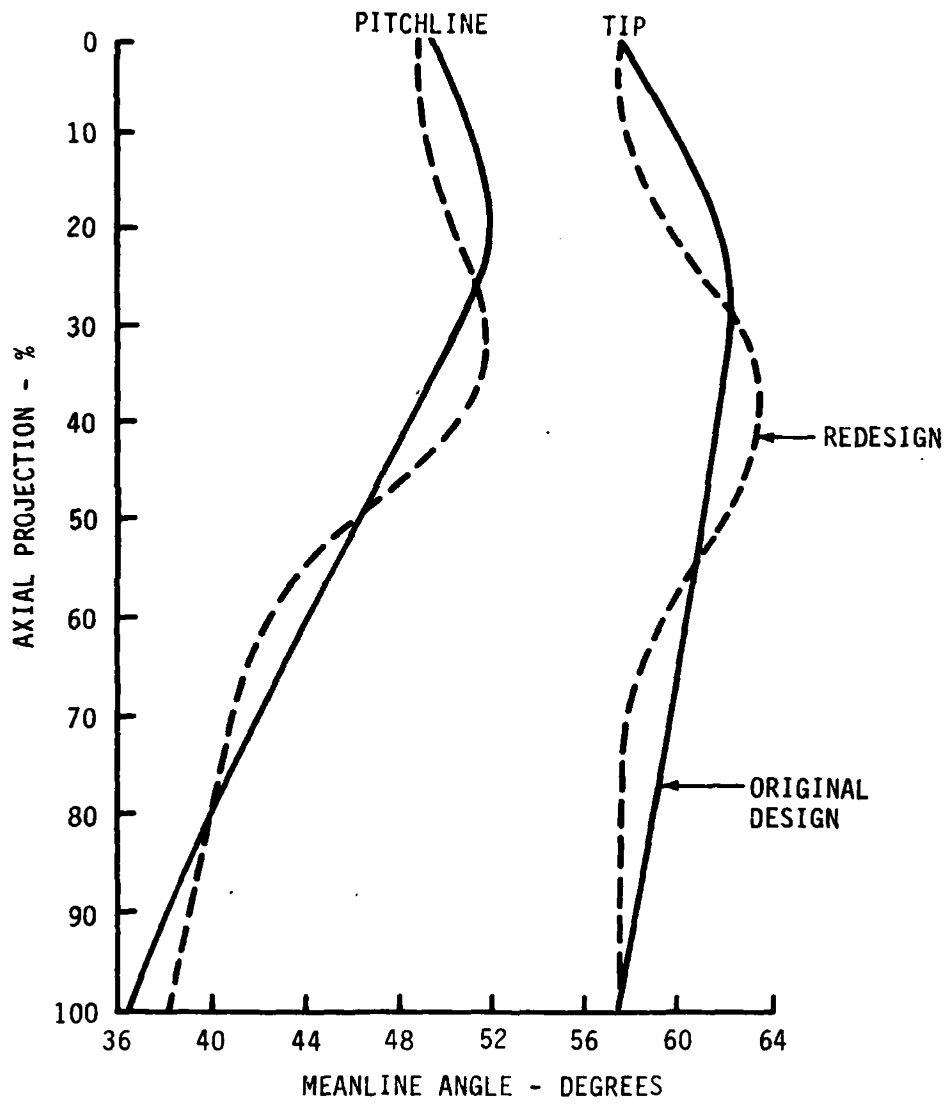

Figure 10. Meanline Metal Angle - Tip and Pitch Sections.

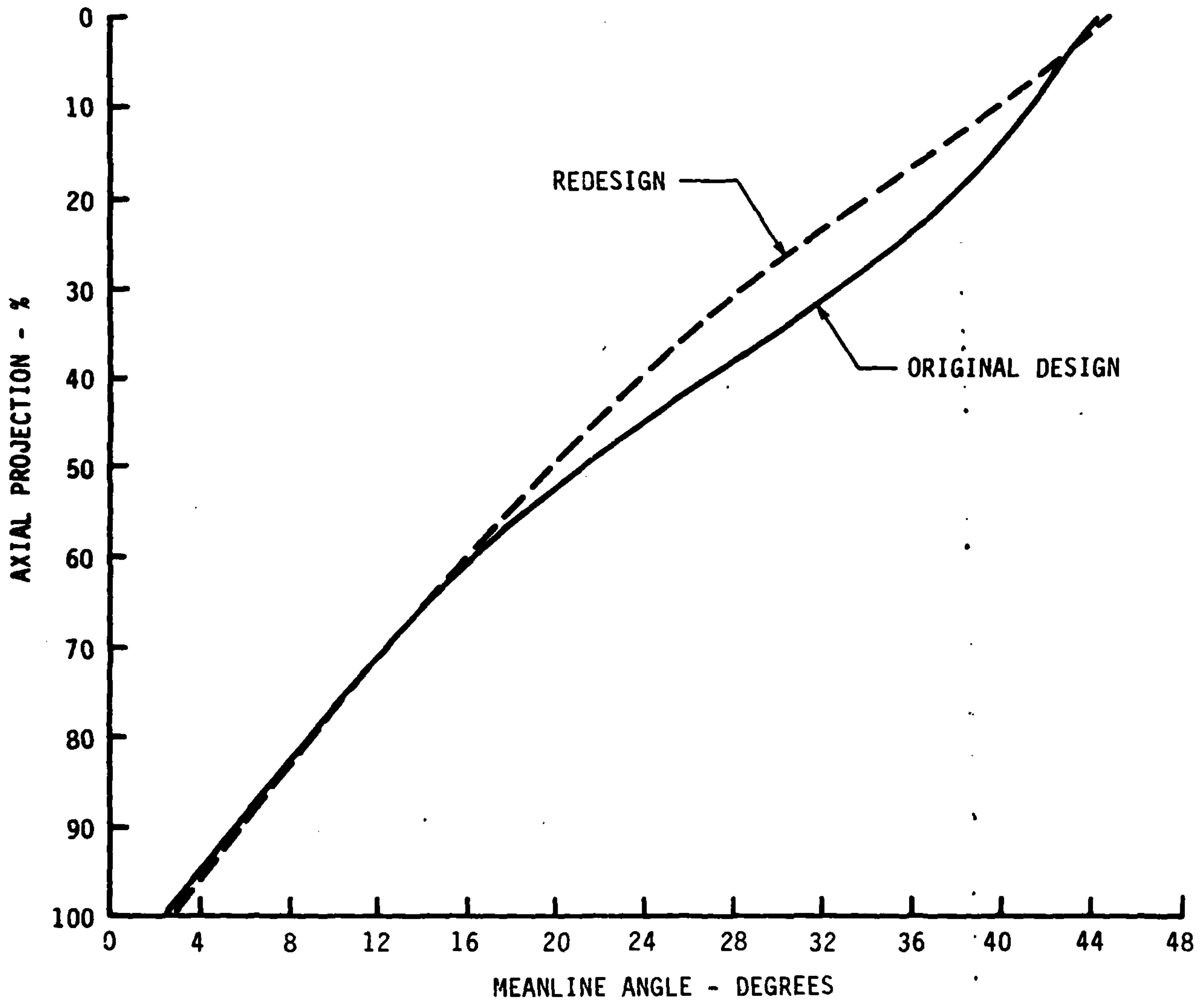

Figure 11. Meanline Metal Angle - Hub Section.

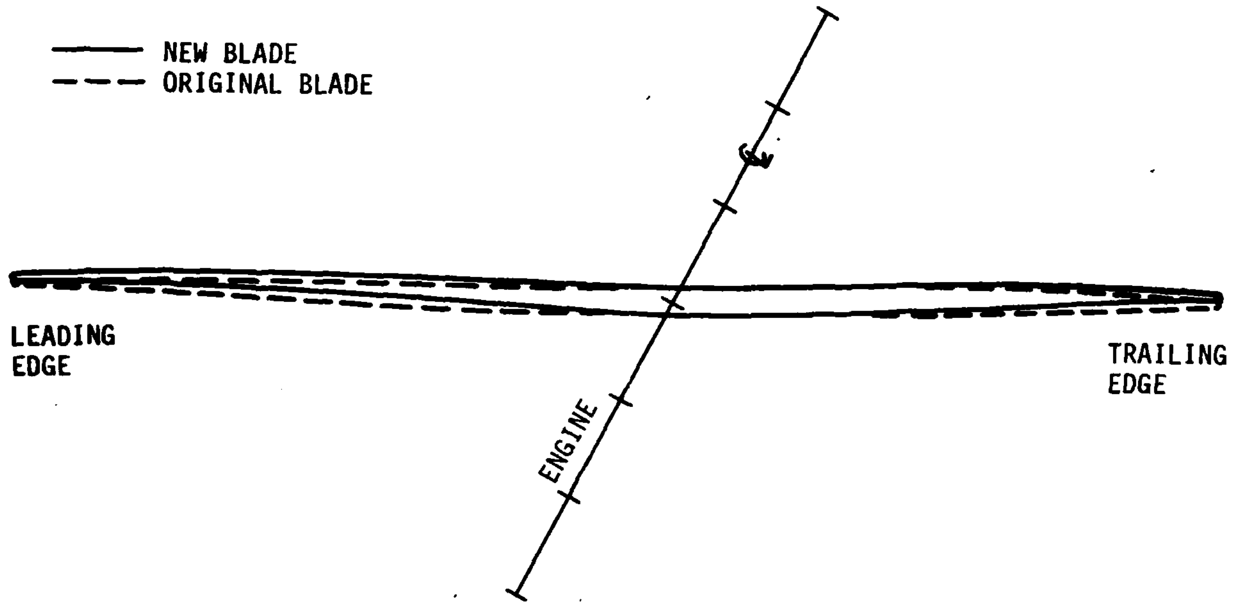

Figure 12. Comparison of New Blade Tip Section to Original Tip Section.

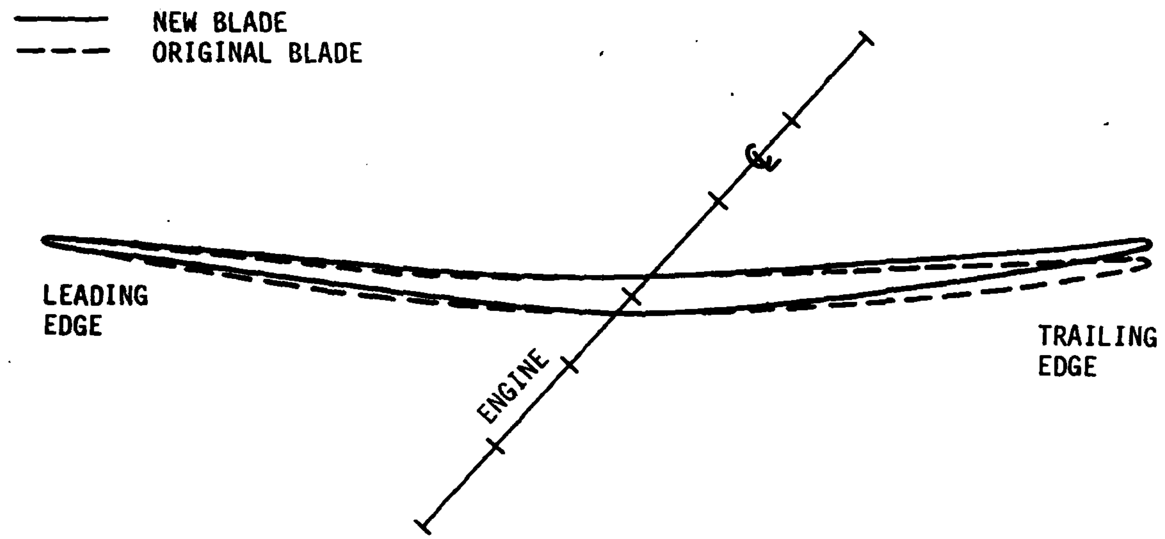

Figure 13. Comparison of New Blade Pitch Section to Original Pitch Section.

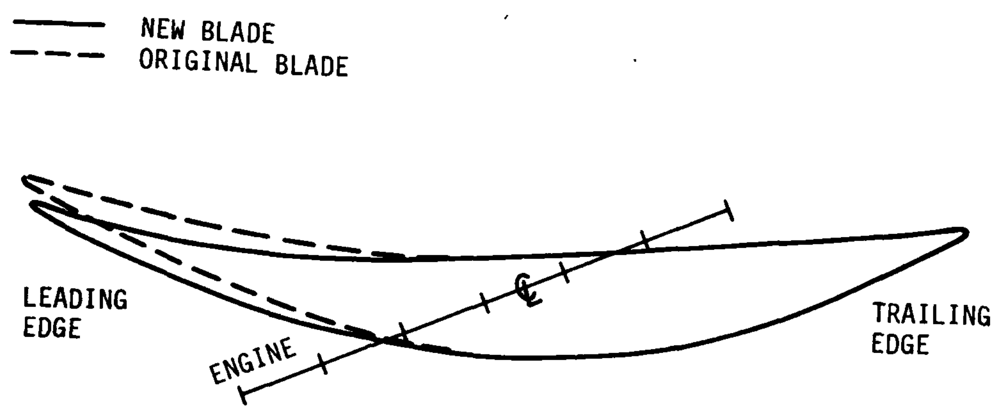

Figure 14. Comparison of New Blade Hub Section to Original Hub Section.

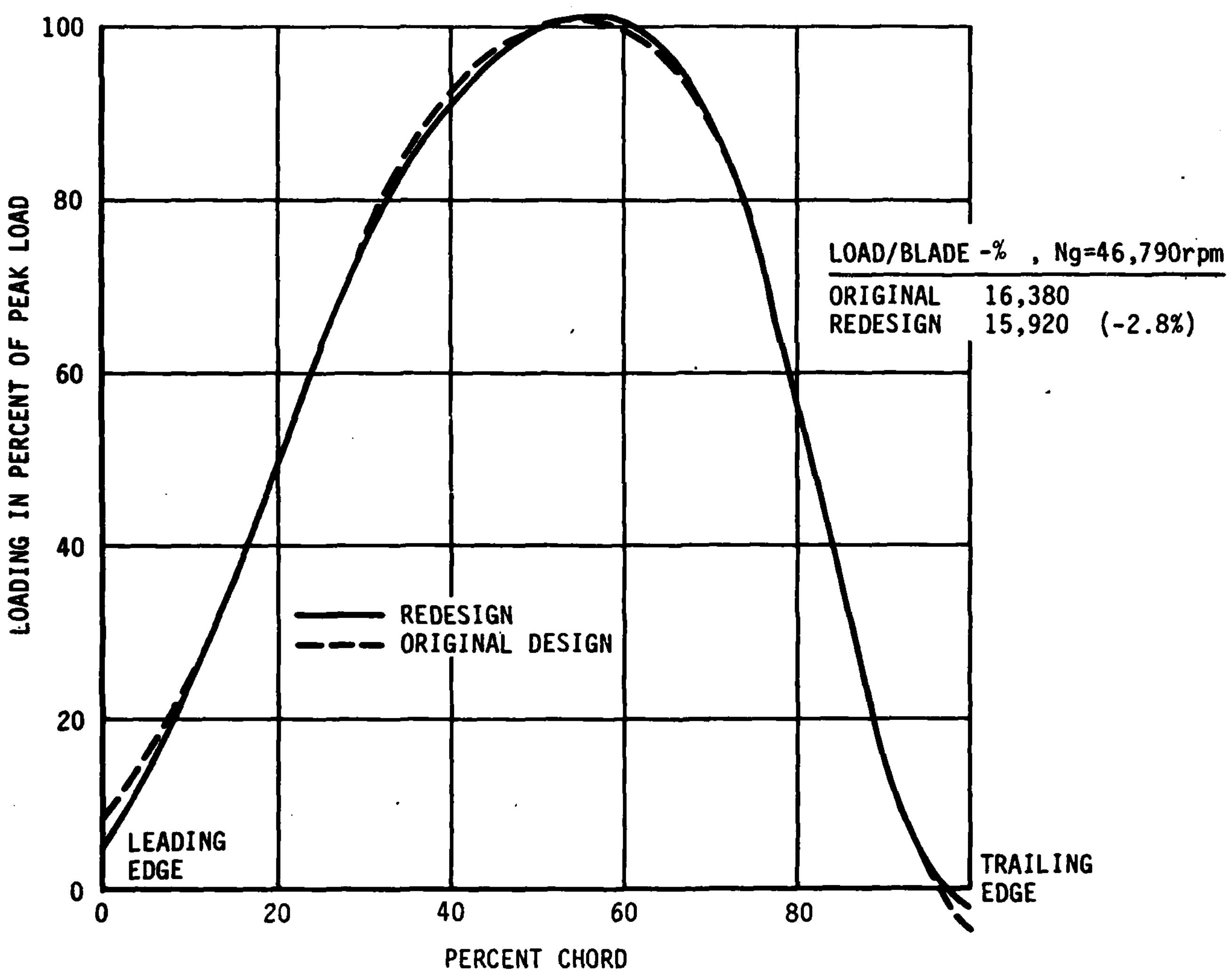

Figure 15. Fan Rotor Load Distribution.

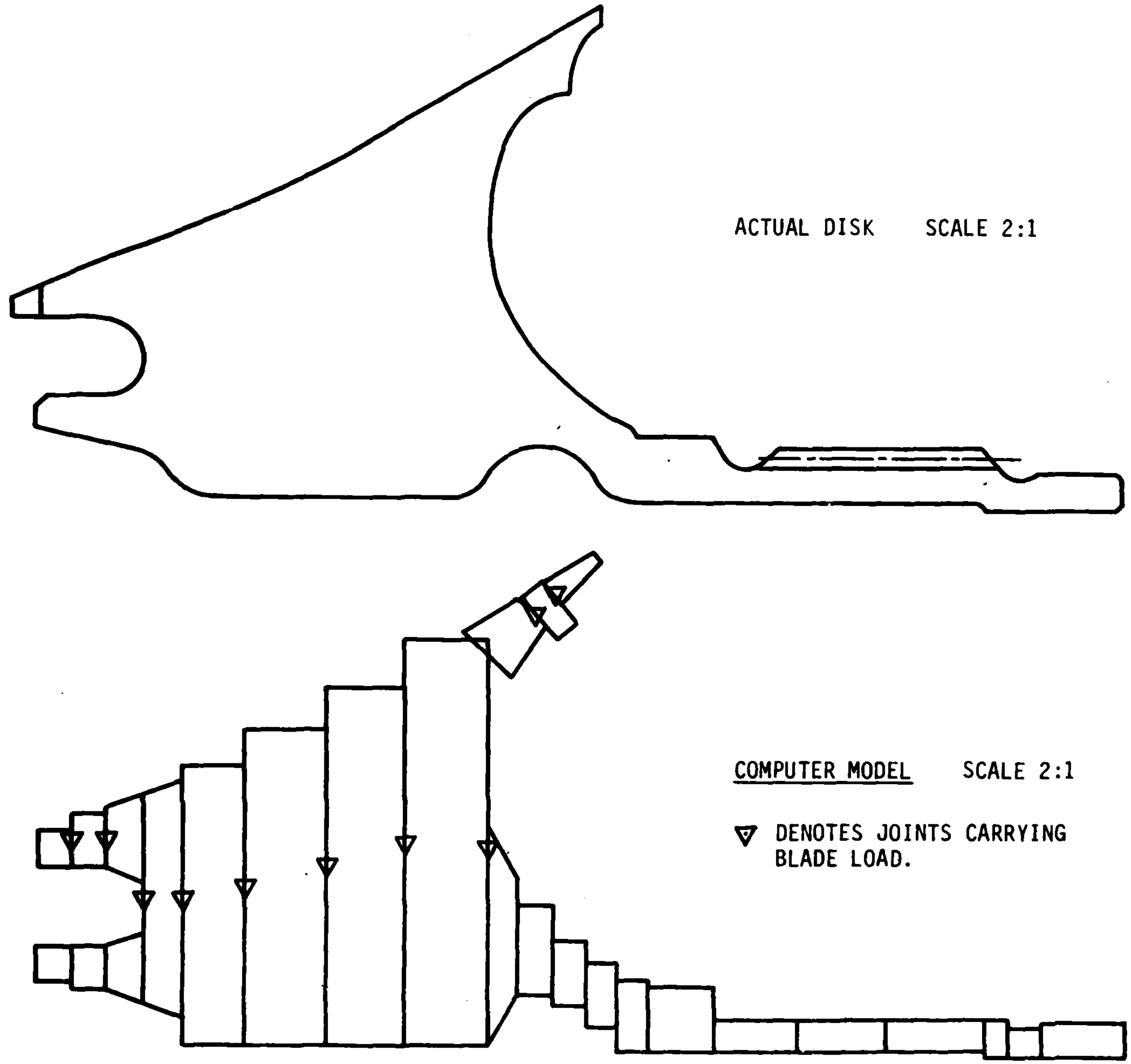

Figure 16. Fan Blisk Stress Model.

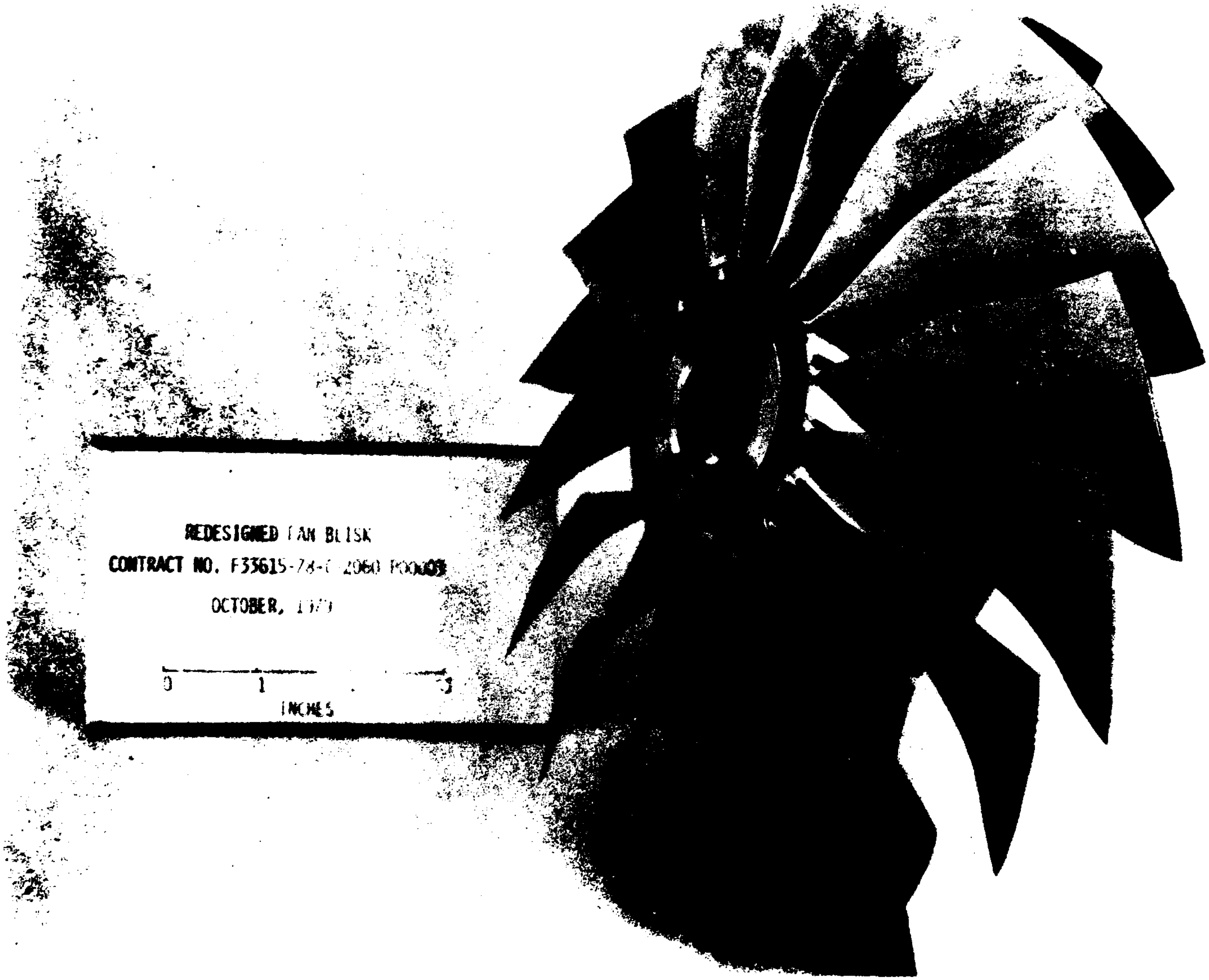

Figure 17. Redesigned Fan Blisk - Three Quarter View.

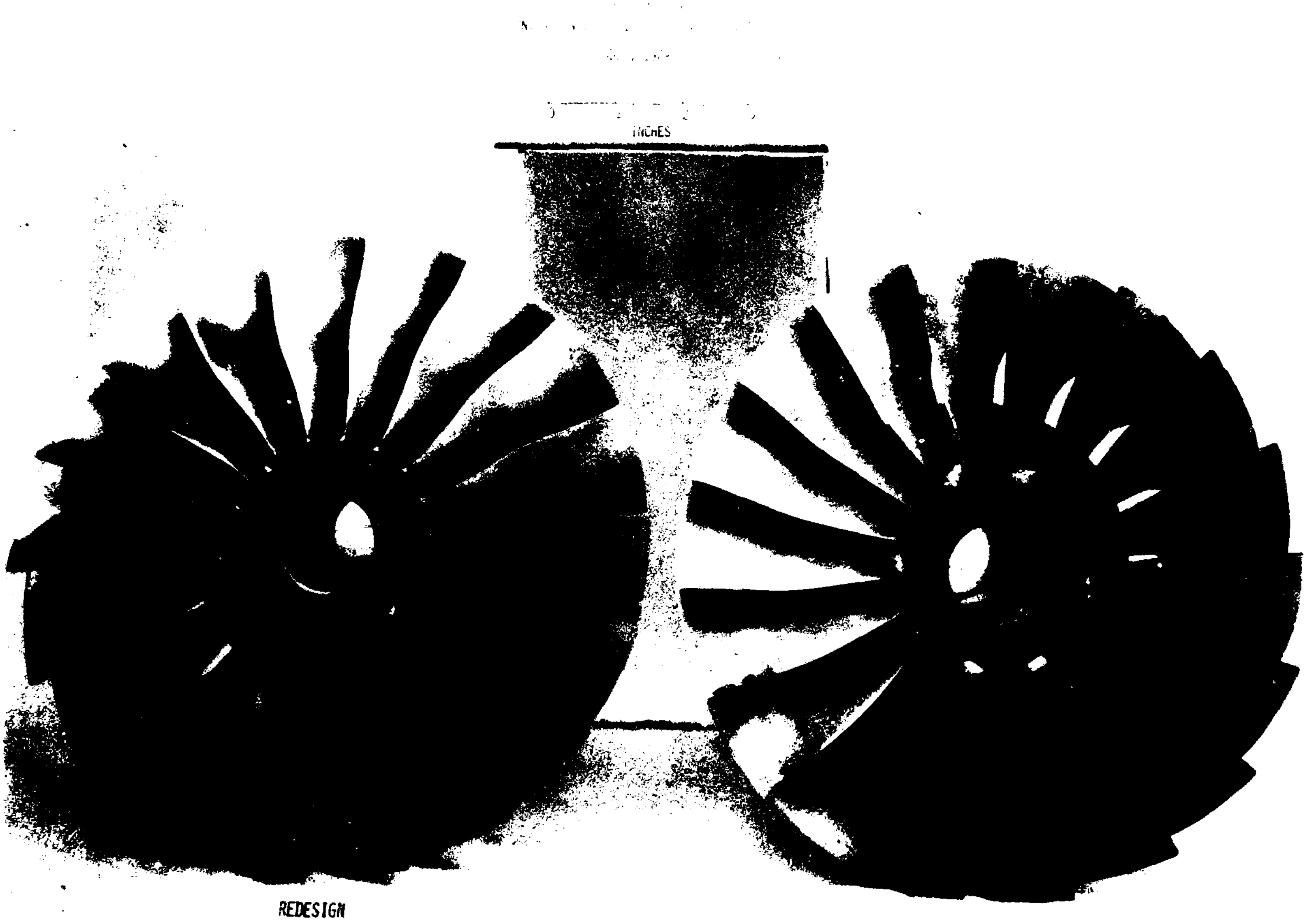

Figure 18. Comparison of Initial and Redesigned Fan Blisk - Front View.

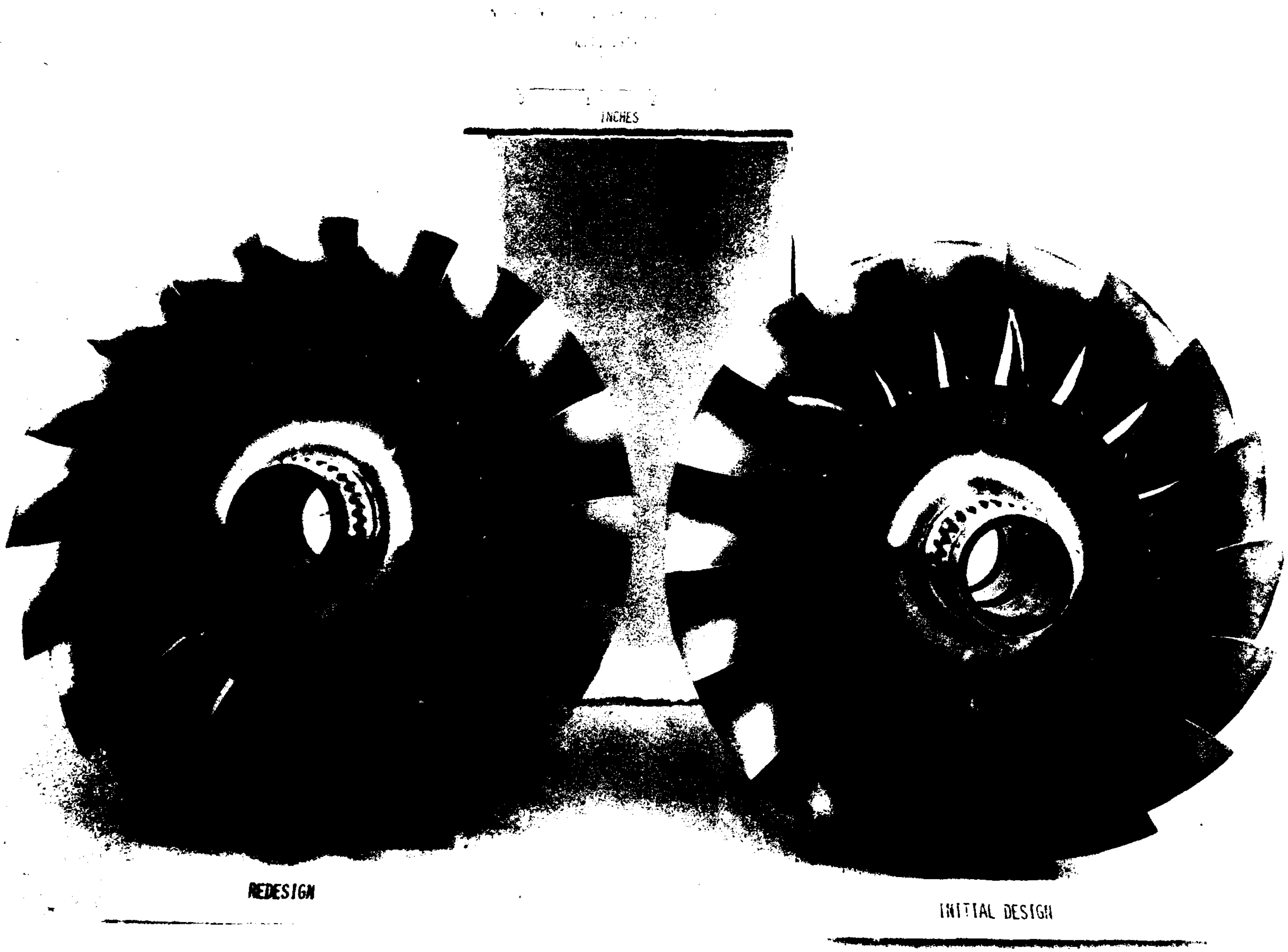

Figure 19. Comparison of Initial and Redesigned Fan Blisk - Rear View.

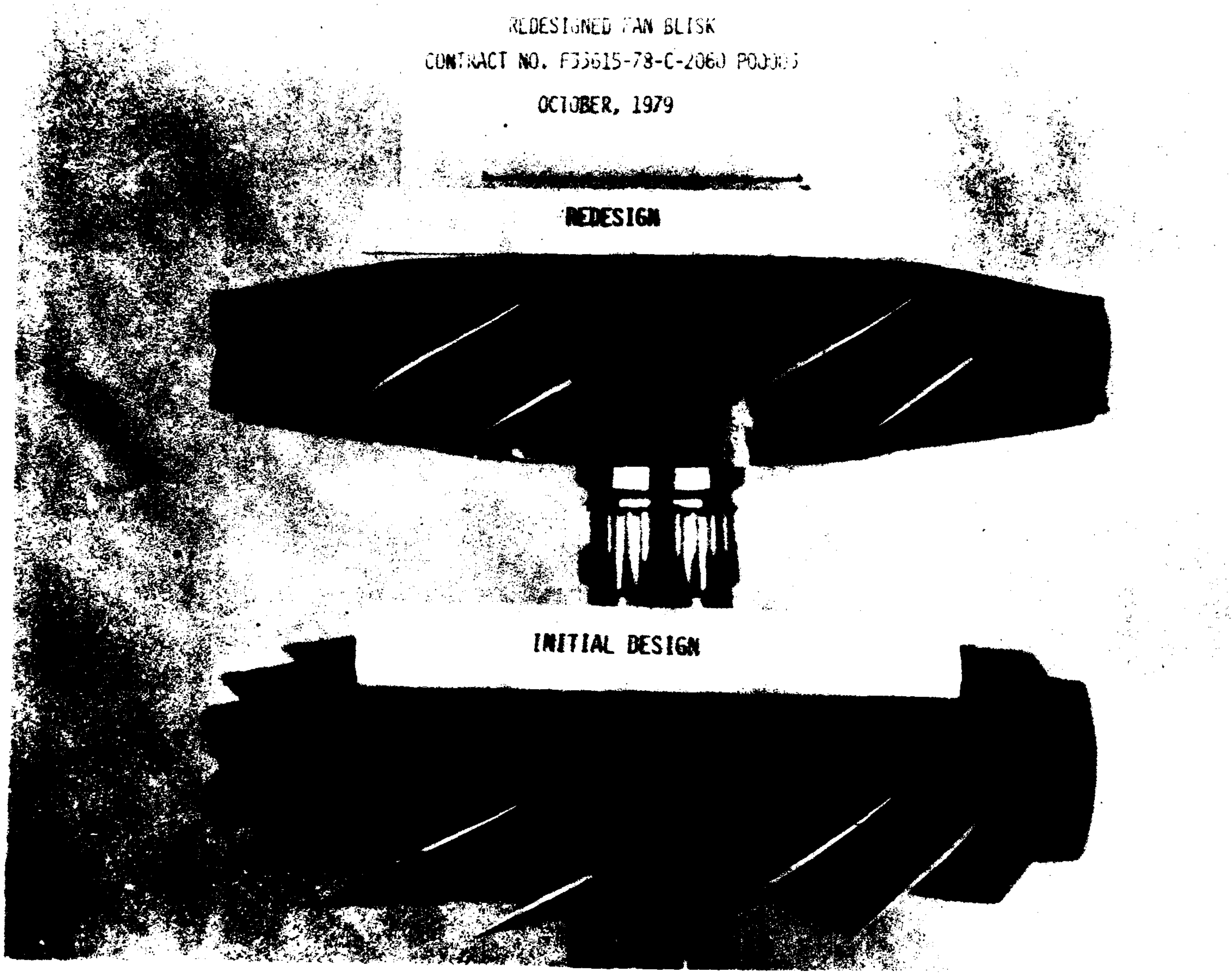

Figure 20. Comparison of Initial & Redesigned Fan Blisk - Side View.